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Thermal performance of a pump-driven loop heat pipe as an air-to-air energy recovery device

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ABSTRACT

A pump-driven loop heat pipe (PLHP) was proposed for energy recovery from exhaust air to reduce fresh air handling energy consumption of air conditioning systems. The influences of working fluid, mass flow rate, heat exchanging area and facing air velocity on heat transfer capacity, temperature effectiveness and coefficient of performance (COP) were studied experimentally under different working conditions. The optimum working fluid and value were obtained, respectively. Results indicate that the heat transfer capacity and COP increase with the temperature difference between indoor and outdoor air while the temperature effectiveness decreases. The general performance for R32 as working fluid was better than R22 and R152a. For summer condition, the heat transfer capacity was 4.09 kW and the COP was 9.26 when the mass flow rate was 250 kg h^{-1}, the heat exchanging area was 58.0 m^2 and the facing air velocity was 1.8 m s^{-1}. For winter condition, the heat transfer capacity was 6.63 kW and the COP was 14.20 while the mass flow rate was 300 kg h^{-1}, the heat exchanging area was 58.0 m^2 and the facing air velocity was 1.8 m s^{-1}. The tested device could meet the energy recovery need with remarkable energy savings.

1. Introduction

The building energy consumption takes about 30% of national total energy consumption in developed countries. The air conditioning energy consumption occupies about 19.5% of the building energy consumption. In China the large public building floor area is only 5–6% of the total town floor area, but the power consumption of large public buildings is over ten times as much as residence buildings with same area [1]. The power consumption of air conditioning systems in public buildings accounts for 50–60% [2]. Buildings using exhaust and fresh air systems for 24 h/day could benefit from air-to-air energy recovery devices. Such recovery devices can reduce energy consumption by transferring 40–80% of the sensible and latent heat between the exhaust air and fresh air streams [3], especially for occasions with polluted air, high indoor air quality requirement, large/full fresh air. The research and development of energy recovery technology or product were carried out in many countries, which focused on energy recovery effectiveness and indoor air quality (IAQ) [4–9]. The energy recovery devices are applied widely in residential and commercial air conditioning systems nowadays [10]. The air-to-air energy recovery device should be set up for concentrated air conditioning systems when it is rational for technical economic comparison [11]. For energy recovery evaluation, the coefficient of performance (COP) should be more than five besides considering the energy recovery effectiveness [12].

Firstly, air-to-air energy recovery device using in fresh air system for room or building includes integral and separated types. The rotary thermal wheels [13,14], plate [15–18], plate-fin [19], heat pump [20,21] and integrated heat pipe [22–30] all belong to the integral type energy recovery device. Both the intermediate working medium chiller and split heat pipe are separated type energy recovery devices. O'Connor et al. [31] analyzed and compared six different heat recovery devices in UK. Heat pipes and rotary thermal wheels were suggested as the mostly potential technologies due to high thermal efficiency and low pressure loss across the heat recovery device in comparison to the other technologies. However, fresh air cannot be isolated from exhaust air in the rotary thermal wheels, so fresh air may be contaminated by exhaust air although its energy recovery efficiency is high.

For the integral energy recovery device owning high effectiveness and COP, the fresh air and exhaust air ducts should be set up closely due to heat exchanger's structure. When fresh air duct and exhaust air duct is apart or there are several fresh/exhaust air ducts, split heat pipe is available but integral heat pipe not. Among the separated energy recovery device, water or glycol is charged

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Nomenclature

A	Heat exchanging area, m^2
COP	Coefficient of performance
d_o	Outer tube diameter, mm
d_i	Inner tube diameter, mm
h_{11}	Inlet air enthalpy of exhaust air heat exchanger, $kJ\,kg^{-1}$
h_{12}	Outlet air enthalpy of exhaust air heat exchanger,$kJ\,kg^{-1}$Outlet air enthalpy of exhaust air heat exchanger,$kJ\,kg^{-1}$
l	Tube length, mm
m	Mass flow capacity, $kg\,h^{-1}$
m_1	Air-side mass flow rate of exhaust air heat exchanger, $kg\,s^{-1}$
n_x	Number of tube rows for facing air
n_y	Number of pipe rows for air
Q	Heat transfer capacity, kW
s_f	Fin spacing, mm
s_x	Tube spacing for facing air, mm
s_y	Tube spacing for air, mm
T_{11}	Inlet air temperature of exhaust air heat exchanger, °C
T_{12}	Outlet air temperature of exhaust air heat exchanger, °C
T_{21}	Inlet air temperature of fresh air heat exchanger, °C
v	Facing air velocity, $m\,s^{-1}$
W_1	Fan power of exhaust air heat exchanger, kW
W_2	Fan power of fresh air heat exchanger, kW
W_3	Pump power, kW
δ_f	Fin thickness, mm
δ_t	Tube thickness, mm
η	Temperature effectiveness, %

Subscripts

1	Exhaust air heat exchanger
11	Inlet of exhaust air heat exchanger
12	Outlet of exhaust air heat exchanger
2	Fresh air heat exchanger
21	Inlet of fresh air heat exchanger
3	Pump
f	Fin
i	Inner
o	Outer
t	Tube
x	Facing air direction
y	Air direction

into the intermediate working medium chiller as the working fluid, and the water pump supplies the circulation driving force. Bennett et al. [32] and Johnson et al. [33] studied the intermediate working medium chiller experimentally and numerically. The full-life cycle cost as a function of initial investment, maintenance cost and annual energy savings was discussed. However, the water or glycol working fluid could be frozen in cold winter. The pump power consumption is huge due to the sensible heat transfer, which results in bad system economy. The split heat pipe is the development of conventional heat pipe, in which the low boiling-point substance is charged as working fluid for phase-change heat transfer assisted with capillary force or gravity. Matsubara et al. [34] revealed that the negative inclination almost halted the heat transfer while the positive inclination showed the performance comparable to the no inclination mode for the cases up to the inclination angle 90°. Liu et al. [35] investigated the rules between energy recovery effectiveness and indoor and outdoor temperature difference, and found that the split heat pipe needed to be started up under some suitable temperature difference. The minimum start-up temperature difference was still needed further study. Besides, the split heat pipe can work while the condenser must be installed higher than the evaporator. Therefore, split heat pipe only runs in summer or winter not for a whole year unless the installation changes. In addition, the weak driving force is another disadvantage of split heat pipe, especially for multi condensers and evaporators system. The pump-driven loop heat pipe (PLHP) with strong driving force is proposed to eliminate both the installation and height difference requirements, and to recover energy from exhaust air in fresh air system in a whole year just switching its running modes. In such system the high efficiency phase-change heat transfer of heat pipe is combined with the powerful driving force of mechanical pump. The charged low boiling-point working fluid does not need anti-freezing. The installation is not restricted to the height difference. The system could run for a whole year for maximum energy recovery.

Secondly, for applications researchers [36–39] including our group [40–42] used the PLHP for free cooling in datacom centers. Compared to conventional vapor compression refrigeration, the energy savings were obvious. The indoor and outdoor temperature difference and mass flow rate were key factors to the heat transfer capacity and COP of the system. Zhang et al. [40] designed and investigated a PLHP for datacom center cooling. The experimental results indicated that the COP was 5.88 at the temperature difference of 10 °C, and it increased to 10.41 at the temperature difference of 18 °C. Ma et al. [41] pointed out that the pump power consumption was the main factor for COP. The power consumption could be reduced by 36.57% through energy-saving analysis with experimental fitting formula. And the test platform for magnetic PLHP was also built up for datacom center cooling [42,43]. The heat transfer capacity increased with the temperature difference, and first increased with mass flow rate and then decreased.

However, the energy recovery in building ventilation is quite different from free cooling in datacom center. The annual heat flux in building energy recovery varies obviously as atmospheric temperature varies, while it owns a little fluctuation in datacom center free cooling. In energy recovery the PLHP device works yearly with two running modes, i.e. summer mode and winter mode, while there is only one running mode in free cooling. The fresh outdoor air is drawn into building to replace the exhaust indoor air, namely air replacement going with heat exchange, while there just is heat exchange in datacom centers. In general, the characteristics of the PLHP device for energy recovery is quite different from the ones for free cooling. And the PLHP energy recovery device can work yearly with advantages of high efficiency at variable heat flux, and ease to switch running mode and no installation limitation.

In the paper, the PLHP energy recovery device for room temperature was designed and developed, which could meet the energy recovery needs in both winter and summer with two-way working fluid cycle. The influences of working fluid, mass flow rate, heat exchanging area and facing air velocity on energy recovery performance were analyzed experimentally.

2. Pump-driven loop heat pipe energy recovery device

The PLHP energy recovery device (Fig. 1) consisted of a pump, fresh air heat exchanger with fan, exhaust air heat exchanger with fan, liquid reservoir and four cut-off valves. The pump was a self-priming magnetic pump with rated power 1.0 kW. The maximum head and speed of the pump were 57 m and 50 L min^{-1} respectively, and the rated speed of the motor was 2800 L min^{-1}. The heat exchangers were fin-tube heat exchangers with the same specifications and placed at the same height. The heat exchangers consisted